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Incised Pleistocene valleys in the Western Belgium coastal plain: age, origins and implications for the evolution of the Southern North Sea Basin

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Abstract

The Belgian coastal plain occupies a key position as it is located at the transition between the Southern North Sea Basin and the Strait of Dover. It is characterised by thick sequences (>20m) of Pleistocene terrestrial and littoral sediments. Yet the wider stratigraphical and palaeo-environmental significance of these sediments received little attention. In this paper we draw on the results of a recent sedimentological study based on >100 drillings that spans the Pleistocene sequence, and present new biostratigraphical (pollen, foraminifera, ostracods) data, all revealing a complex history of deposition. The record includes evidence of the development of incised-valley systems that were initiated in the late Middle and Late Pleistocene. Five phases of fluvial incision can be identified. The majority of the infills are deposited in an estuarine environment that passes into a fluvial environment land inward, except the Weichselian infill which has a predominant fluvial origin. The greatest part of the most seaward located zone of the western coastal plain was free of valley incisions, there, shallow marine sediments built up the record. Local biostratigraphical investigations provide a timeframe. The result are placed in a regional context.

Keywords: complex incised-valley system, valley fill, estuarine, fluvial, pre-Eemian.

1. Introduction

The western coastal plain of Belgium (Fig. 1) is characterized by a thick (>20 m) accumulation of Pleistocene sediments, which extend about 20 km inland. The deposits have never been studied in the context of the Pleistocene evolution of the Southern North Sea Basin. The few existing studies concern local investigations (e.g. Denys et al., 1983; Tavernier and de Heinzelin, 1962; Vanhoorne, 1962, 2003). That the Pleistocene deposits along the whole Belgian coast consist of littoral deposits, locally covered with Weichselian fluvial and/or aeolian deposits, is widely accepted. It is believed that the littoral deposits only extend back to the Eemian Stage and linked to one transgressive phase (Baeteman, 1993; Denys et al., 1983; Mostaert and De Moor, 1984; Mostaert et al., 1989 and Paepe, 1971), with the exception of the deposits in the area nearby the city of Lo to which a Holsteinian/Cromerian age is given (Vanhoorne, 1962, 2003). The idea that the Quaternary geological history of the western coastal plain, and even the entire Belgian coastal plain, is so simple and as young as the Eemian contradicts evidence from neighbouring countries of the Southern North Sea Basin where older littoral deposits of Middle Pleistocene age have also been described (e.g. Balescu and Lamothe, 1993; Bates et al., 2003; 1999; Roe et al. 2009; Roe and Preece, 2011; Sarnthein et al., 1986; Sommé et al.,2004). One hundred and five undisturbed mechanically drilled cores covering the whole Quaternary sediment succession provided the opportunity to make a cohesive and comprehensive sedimentological and morphological study that has led to new insights on both local and regional scale. A multidisciplinary approach is used whereby the sedimentological interpretations are supported by foraminiferal, ostracod and pollen analyses. A pollen record from a borehole at Woumen, near Diksmuide in the west of the area is described, and foraminiferal and ostracod analyses are presented from six cores from the northern, central and southern parts of the region (Fig 1). The new morphological, litho- and biostratigraphical findings show the presence of a complex incised-valley system in the western coastal plain as a result of a series of erosional and depositional phases, controlled by terrestrial and marine processes. Those processes span the late Middle and Late Pleistocene. As the western coastal plain occupies a transitional position between the largely depositional area of the Southern North Sea and the predominantly erosional Strait of Dover region (cf. Gibbard, 1988, 1995, 2007; Gupta *et al.*, 2007; Hijma *et al.,* 2012) the findings also provide additional insights into the late Middle and Late Pleistocene development of the wider Southern North Sea Basin.

2. Geographical and geological setting

2. 1. Study area

The western coastal plain (WCP) lies on the margin of the southern North Sea in the northwest of Belgium, extending from the border with France to Oostende in the north, and from Diksmuide to Lo-Reninge and Merkem in the south (Fig. 1). The coastal area is drained by the River IJzer, which rises in France, and its tributaries the Kemmelbeek and Sint Jansbeek, both having their source in Belgium (Fig. 1). A significant dune system extends along much of the coastal region. This has been locally downgraded by development and aggregate extraction. Because of embankments, the coastal plain today forms a low-lying, flat artificial landscape with sluices, ditches and canals. Its land surface ranges from +1 m and +5 m TAW, (TAW ordnance datum and refers to mean lowest low-water spring at Oostende, i.e. *ca*. 2 m below mean sea level - Agency for Maritime Services and Coast-Division – COAST) which is below high water level. The plain is protected from flooding by the remaining dunes and locally by seawalls. The present-day landscape results from a continuous infill process controlled by sea-level rise during the Holocene (Baeteman, 1999, 2013). The modern topography thus masks the Pleistocene coastal and continental deposits that underlie the Holocene infill. The Pleistocene sediments in turn overlie Paleogene deposits of Eocene age. The Pleistocene sedimentary record is predominantly composed of shore-shelf, tidal and fluvial deposits, each depositional unit showing a variety of lithofacies and architectural elements (Bogemans, 2014; Bogemans and Baeteman, 2014). The textural composition ranges from coarse to fine sediments (gravel to clay). The gravel component is mainly composed of shell remains, with subsidiary siliciclastic particles. The rest of the deposits are mainly siliciclastic.

2.2. Research history

Previous studies have mainly described the fossiliferous Pleistocene sediments of the WCP. Tavernier and de Heinzelin (1962) and Vanhoorne (1962, 2003)), for example, describe palaeontological investigations that were undertaken on deposits from the western margin of the WCP near Lo and from the Vinkem–Izenberge area, the latter known as the Izenberge Plateau, and bordering the coastal plain (Fig. 1). At both localities Tavernier and de Heinzelin (1962) observed shell-bearing sediments between +1.45 m to +12.2 m TAW. The associated molluscan assemblages were dominated by small-sized *Cardium edule*, now known as *Cerastoderma edule* (Linnaeus, 1758), along with *Macoma baltica* (Linnaeus, 1758), *Hydrobia stagnalis* (Baster, 1765) and *Theodoxus fluviatilis* (Müller). The authors noted the similarity between these faunas and those found today along the Belgian coast and estuaries and ascribed them to an interglacial or interstadial phase. Furthermore, they concluded that the stratigraphical position and elevation points to a Middle Pleistocene age. Similarly, Vanhoorne (1962, 2003) investigated the palynology and the chronostratigraphy of a peat unit that occurs in Lo beneath the shell-bearing layer observed by Tavernier and de Heinzelin (1962). In the so called “shell-bearing layer” in Lo the molluscan remains are often broken and form part of a predominantly siliciclastic sand deposit (Tavernier and de Heinzelin, 1962). Vanhoorne (1962), initially concluded that the peat accumulated during the Holsteinian Stage, although he could not rule out an interglacial within the Cromerian Complex. However, in 2003 he reassigned the peat bed to the Cromerian IV Substage, and attributed the overlying shell-bearing layer to the Holsteinian (Table 1). Also in 2003, Vanhoorne observed a distinct faunal succession within the shell-rich stratum in the vicinity of Lo (+1.65 - + 2.55 m TAW). Freshwater molluscs and ostracods were observed at the base of the studied unit, whilst brackish and marine species were present at the top, dominated by the mollusc *Cerastoderma glaucum* (Poiret, 1789) and by the foraminiferal species *Ammonia beccarii* (Linnaeus, 1858), *Nonion depressulum* (Walker & Jacob, 1798*)*, *Elphidium exvavatum s.l. Terquem, 1875*, *Elphidium selseyenese* (Heron-Allen & Earland, 1919) and *Elphidium margaritaceum* (Cushman, 1930).

The multidisciplinary palaeontological study of Denys et al. (1983) was based on drillings from near De Panne at the present coast (Fig. 1) and carried out as part of a hydrogeological survey of the Pleistocene deposits. Diatom analyses confirmed that the species composition was similar to that found today in the littoral section of the southern North Sea. However, some diatoms were associated with both warmer and colder environments (Denys et al., 1983). In addition, the samples yielded abundant marine molluscs, although terrestrial and freshwater species were also present. The appearance of Chenopodaceae pollen in all samples, re-affirmed according to Denys et al. (1983) the littoral origin of the sediments. The sequence was assigned to the late Eemian Stage notwithstanding the predominantly sandy nature of the sediments, which yielded only poorly preserved pollen that did not permit firm biostratigraphical correlations, and the stratigraphical uncertainties associated with twenty-one stratigraphically undiagnostic molluscan species (Spaink and Sliggers in Denys et al., 1983) (Table 1).

Lithostratigraphically the marine sediments are named in Belgium the Oostende Formation and defined as tidal and subtidal sand deposits, tidal mudflats and storm beach deposits (Gullentops et al., 2001) (Table 1). The marine deposits underlying the northern French coastal plain near the Belgium border are ascribed by Sommé et al. (2004) and Sommé (2013) to the Loon Formation and correlated with the Oostende Formation on the basis of the similar character of the sediments and their stratigraphic position. An Eemian age is also given (Table 1).

Furthermore in northern France, at Herzeele (Fig. 1), exposures of interglacial coastal and shallow marine sediments have been studied intensively. Sommé et al. (1978) proposed a stratigraphic correlation of the deposits in Herzeele with the shell-bearing deposits described by Tavernier and de Heinzelin (1962) in Lo and Vinkem-Izenberge. However Baeteman (Sommé et al.,1978) and later Paepe et al. (1981) expressed doubts regarding the chronostratigraphic precision of the correlation between these deposits. Baeteman carried out about 100 hand drillings in a north–south corridor from Bulskamp to Roesbrugge-Haringe (Fig. 1) in order to identify the extension of the Herzeele Formation in Belgium. In particular, she paid attention to the distribution of *Cerastoderma edule* in the sediments as this species are described as being dominant in both Herzeele and Lo/Vinkem-Izenberge (Sommé et al.,1978; Tavernier and de Heinzelin, 1962). In the said corridor, only fragments of bivalves and no articulated specimens like those at Herzeele were observed. The occurrence of *C. edule* was also limited, especially in the deposits present beyond the border of the Izenberge Plateau. All the other molluscan taxa recovered were also fragmented, except freshwater molluscs. The shell fragments were concentrated in several rather thin strata between +13 and - 1m TAW (Baeteman in Sommé et al., 1978).

Pollen analysis of the peat beds underlying the shell-bearing bed at Herzeele by Vanhoorne (Sommé et al., 1978) prompted a biostratigraphic correlation with both the shell-bearing bed and the peat beds near Lo. In Vanhoorne and Denys (1987) the shell-bearing bed retains that correlative Holsteinian age as stated in 1978 by Vanhoorne while the underlying deposits including the peat beds are supposed to be older; most probably Cromerian.

Absolute dating of the shell-bearing bed of the Herzeele Formation at its type locality in Herzeele yielded a different age depending the dating techniques. The thermoluminescence determination gave an age of 228 ± 30 ka or preliminary corrected 271 ± 36 ka (Balescu and Lamothe, 1993) whereas the Th/U and ESR analyses gave an age between 300 and 350 ka (Sommé et al., 1999).

3. Methods

One hundred and five high-quality undisturbed continuous mechanically-drilled cores were recovered from the WCP. The cores span the Holocene and Pleistocene sediment succession and extend into the underlying Paleogene substratum. Bogemans and Baeteman (2014) introduced a series of newly identified lithofacies based on the sedimentary characteristics of the deposits observed in the undisturbed cores. These provided a basis for reconstructing the depositional environments of the area. Bogemans (2014) described and interpreted the Pleistocene deposits of each core using the new facies-based classification. Emphasis in this paper is placed on the correlation of the individual core data to develop a wider model of the regional facies architecture. This in turn is used to reconstruct the Pleistocene depositional history and palaeogeography of the WCP. An essential step in this process is the development of a series of integrated cross-sections that are constructed to provide a spatial overview.

The biostratigraphical data used in the study are based on findings from an unpublished report by Roe (1999) that describes pollen, foraminifera, ostracod and molluscan analyses undertaken within the framework of an earlier project on the Pleistocene sediments of the Southern North Sea region, and on foraminifera and ostracod analyses by Bates (2011).

4. Results

This section describes the depositional facies of the study area, the subsurface morphology, the results of the palaeontological analyses from cores and finally, the history of the valley incisions and infillings.

4.1. Sedimentology

Three depositional environments are recognized.

4.1.1. Deposits from shore-shelf environments

In the study area the shore-shelf system comprises shallow marine deposits and outer estuarine deposits. Both consist mainly of shell-rich and sand facies. The shell-rich facies are composed of matrix-supported shell remains (fragments and finely comminuted particles - ‘shell grit’) with and without sand intercalations. Pebble-sized siliciclastic sediments may be present as well as mud clasts. Sporadically mud occurs in thin layers. If stratification is visible, low angle cross-bedding predominates. The sand facies consist of fine to medium grained particles, both massive and bedded, with a predominance of horizontal and low-angled stratification. Shell remains as well as mud laminae are observed, but also deformation and bioturbation structures. If both shell-rich and sand facies are present within one sequence, the sand facies generally overlie the shell-rich facies.

4.1.2. Deposits from tidal environments

These include all deposits associated with coastal and estuarine environments and have a wide distribution in the area, especially those associated with an estuarine environment. Supratidal, intertidal and subtidal deposits are recognized, each with specific textural and sedimentary characteristics. These facies are quite well understood owing to the availability of numerous Holocene analogue observations from the same study area (Baeteman, 2013). The supratidal deposits are composed of fine siliciclastic sediments with variable clay and silt content. They are massive or stratified and contain organic remains. Humic horizons may occur locally. Coarser sediments, especially shell fragments, are exhibited as fine beds or scattered in the deposit. The intertidal deposits comprise mud flat, mixed flat and sand flat deposits. Mud flat deposits are dominated by clay and/or silt, and are mainly massive in structure, although few beds or discontinuous and continuous laminae of coarser material are not exceptional. Deformation structures and bioturbation structures are commonly observed. The mixed flat deposits consist of alternating complexes of contrasting lithologies (from sand to clay), of which the interlayered bedding is either regularly or irregularly spaced. All components of the alternating complex are internally stratified. Bioturbations and deformation structures may occur. Shell grit, deposited as laminae, very thin beds or scattered in the facies, is not uncommon to be encountered.

In the sand flat deposits fine grained sand predominates, which is stratified and partly massively bedded. Clay-silt laminae, most often discontinuous and dispersed, and/or clay clasts are present. Exceptionally, laminae with peat detritus are seen. Shell grit or fine clastic sediments are observed concentrated along foresets or on top of ripple marks. Deformation and bioturbation structures also occur. The subtidal deposits comprise fine to medium stratified and partly massive sand in which clay and silt laminae may be present, concentrated in a composite bedset or spread through the facies. Shell grit, peat detritus and fine gravel are seen, as well as deformation structures and bioturbations. The lower part of a subtidal deposit is often heterogenic and composed of sand, gravel size siliciclastic material and shell remains. The uppermost horizons, if not completely eroded, are sometimes characterised by one or several small fining up sequences.

4.1.3. Deposits from fluvial and fluvial-tidal environments

These facies include fluvial deposits *sensu stricto* and deposits that accumulated in the transitional or inner part of an estuary where the depositional processes are predominantly fluvial. The fluvial sediments are aggraded within channels or on overbanks (following the definition of Miall, 1996). The sedimentary characteristics point to deposition by different river types. The prominent presence of fine-grained deposits especially silts, is particularly noteworthy. They are not only related to overbank environments but are also the main component of the channel facies. The latter typically show fine ripple and horizontal to oblique bedding structures. In the overbank deposits, climbing ripples prevail. The style of the associated river is unknown. Most of the other channel deposits are predominantly sand dominant and linked to both meandering and braided rivers. A detailed description is given in Bogemans (2014). Coarse grained fluvial deposits are also occasionally encountered. These are mainly composed of shell fragments and peat clasts in a sand matrix. Within the fluvial facies organic beds of peat and gyttja are observed, however their distribution as well as the thickness is locally restricted.

The fluvial – tidal deposits have a grain-size distribution ranging from sand to clay. Inclined heterolithic stratification is commonly observed as well as reactivation surfaces. Vegetation remnants, deformation structures and calcium carbonate precipitates may occur.

4.2. Subsurface morphology and the existence of erosional surfaces

The top of the Paleogene substratum displays a largely N – S oriented depression from Ramskapelle further to the south. The thalweg of the depression runs via Oostkerke to Nieuwkapelle (Fig. 2). The depression is funnel shaped with an increasing width towards the north. Especially in the western part of the WCP a terrace-like morphology is visible. In the most seaward area north of Koksijde, Ramskapelle and Mannekensvere, the top of the

Paleogene substratum shows a series of SW – NE oriented ridges separated by small depressions (Fig. 2).

The numerous cross-sections, constructed in the framework of this study, confirm the existence of a series of regional erosional surfaces within the depositional records. Both the terrace levels and the regional erosional surfaces are correlated with fluvial incision phases that generated incised-valley systems (cf. Dalrymple *et al*., 1994; Zaitlin et al., 1994).

4.3 Palaeontology

4.3.1 Foraminifera, Ostracoda and Mollusca

Two sediment cores collected from the northern part of the study region, Rattevalle (36W168) and Leeuwenhof (36E132) (Figs. 1, 8) yielded over 20 species of foraminifera and ca. 40 species of ostracods (Tables 3, 4). The samples were taken from the outer estuarine deposits of the Rattevalle core and the tidal deposits of the Leeuwenhof core (Table 2), the latter showing sedimentological evidence for freshwater input on several levels in the sequence (Bogemans, 2014). The foraminifera and ostracods of the Rattevalle core (Tables 3, 4) include several large and robust species, perhaps suggesting transportation, sorting and/or reworking. The foraminifera are for the most part 'warm' climate species that occur in open estuarine environments and shallow coastal waters, including *Elphidium crispum* (Linnaeus, 1758), *Elphidium fichtellianum* (d'Orbigny, 1846), *Ammonia batavus* (Hofker, 1951) and *Ammonia falsobeccarii* (Rouvillois, 1974). Inner estuarine and mudflat dwelling species are generally less well represented, although the presence of *Trochammina inflata* (Montagu 1808) in several samples points to the proximity of a saltmarsh. The ostracod assemblage is also composed of 'warm' loving species and consistent with an estuarine environment with open access to the sea.

With the exception of the samples below 12.28 m, in the Leeuwenhof core (Tables 3, 4) many of the samples yielded a few ostracod species that are able to tolerate cooler-water conditions, such as *Leucocythere batesi*, (Whittaker and Horne, 2009), *Limnocythere falcata* (Diebel, 1968), *Limnocytherina sanctipatricii* (Brady and Robertson) and *Cytherissa lacustris*, which are freshwater species.

The microfossil assemblages confirm the lithofacies interpretations (Table 2). In the case of the Rattevalle core an outer estuarine environment is supposed with high-energy shell banks, whereas at Leeuwenhof open estuarine conditions are indicated, fringed with mudflats and backed by salt marshes and freshwater habitats.

The Zoutenaaie (51W142) and Reiger (51W150) cores (Fig. 1) are situated in the central part of the plain. The number of species is strongly reduced in comparison to the Rattevalle and Leeuwenhof records (Tables 3, 4). In the Zoutenaaie core, the dominance of brackish foraminifera and both brackish and freshwater ostracods conforms the lithofacies reconstructions that suggest that the sediments were deposited near the upper limit of tidal penetration in an estuary (Bogemans, 2014 and Table 2). The presence of the freshwater ostracod *Scottia browniana* (Jones) at a depth of 15.25 – 15.27 m in the assemblage is worth mentioning (Bates, 2011). This species has been reported in a small number of Middle Pleistocene interglacial sites in southern England, but is widely believed to have become extinct after MIS 11 (Robinson, 1979; Roe, 2001; White et al., 2013).

The samples from the Reiger core between - 11.91 and - 11.93 m TAW (15.26–15.28 m below the surface) yielded a rich microfauna comprising brackish and outer estuarine/marine foraminifera, and brackish to outer estuarine/marine and freshwater ostracods (Table 3, 4). The assemblages together suggest that the deposits represent the landward part of an estuary with tidal currents bringing in outer-estuarine and/or marine species.

The samples from the Lollege core (51W138) in the southwest of the region (Fig. 1) were taking in tidal deposits (Table 2). The foraminifera and ostracod-bearing samples all lie above 0 m TAW (between 1.35 and 2.36 m beneath the surface). Foraminifera were again abundant, and diverse assemblage (10 species) was recorded (Table 3). The assemblage as a whole is indicative of an estuarine environment that was subject to full tidal mixing. The marine and outer estuarine foraminiferal species represented, include *Elphidium excavatum* (Terquem), *Trifarina angulosa* (Williamson, 1858*)*, *Elphidium margaritaceum*, *Lobatula lobatula* (Walker & Jacob, 1798) and *Elphidium crispum* (Linnaeus, 1758) whilst *Ammonia* sp. and *Haynesina germanica* (Ehrenberg, 1840) are diagnostic of brackish-water and tidal flat habitats. The presence of occasional freshwater ostracods and the absence of saltmarsh forams or ostracods in the assemblage attests to distal freshwater inputs.

Samples from the Woumen core (51E162) (Fig. 1,) yielded several species of brackish water foraminifera which were most abundant between 5.10 and 5.84 m, including *Ammonia* cf. *beccarri* (Linnaeus, 1758), and *Haynesina germanica*, *Elphidium williamsoni* (Haynes, 1973) and *Elphidium gerthi* Van Voorthuysen, 1957 (Table 3). Low numbers of brackish water ostracods were also found at 8.63 m from sediments assigned to fluvial overbank deposits with tidal influence (Table 2). A single valve of the euryhaline ostracod *Cyprideis torosa* (Jones, 1850) was noted at 10.90 m (Table 4).

None of the cores yielded any biostratigraphically diagnostic *in situ* microfossils. The only specimen of stratigraphical interest is *Scottia browniana* although a pre-MIS 9 age is hard to reconcile. The single specimen of *S. browniana* may have been reworked from older interglacial deposits from either the Herzeele region, the source area of the IJzer river at that time, or from older, more elevated Middle Pleistocene deposits near Vinkem - Izenberghe. It should also be noted that the temporal distribution and biostratigraphical significance of this species may also differ in continental Europe to that inferred in Britain.

4.3.2. Pollen and other palynomorphs

Samples were processed for pollen analysis from between 1.50-11.60 m in the Woumen core (51E162) (Fig. 1); the Holocene-Pleistocene boundary in this core lies at 2.20 m beneath the surface. The pollen assemblages recovered from 1.50-1.85 m included arboreal elements (particularly high frequencies of *Tilia*), that confirm a mid-Holocene age (Roe, 1999). The pollen content from 1.85 -4.26 m was sparse, but 11 samples from a dominant peaty deposit from between 4.54 -7.28 m, yielded sufficient pollen to obtain full counts (Fig. 3). The samples from the underlying fluvial-tidal deposits (7.35 m to 11.60 m) generally only gave sparse pollen (Table 2). At the base of the core, from 10.90 m and deeper, 3 samples showed an interglacial tree pollen assemblage of low concentration (Table 5).

The pollen assemblages from 4.54-7.28 m were divided into three local pollen assemblage biozones: Wo-1 (7.28 to 7.02 m), Wo-2 (7.02 to 6.15 m) and Wo-3 (6.15 to 4.54 m). Biozone Wo-1, which is associated with sand below 7.20 m and peats above this depth (Fig. 3), is dominated by *Corylus* (35%) and *Pinus* pollen (23%). *Quercus* also occurs at moderate frequencies (18-21%), along with low percentages of *Ulmus* pollen. *Alnus* is present at low but persistent frequencies, whilst pollen of *Tilia*, *Acer*, *Fraxinus* and *Betula* occurs intermittently. Shrubs are restricted to sporadic occurrences and herbs include Poaceae (5%), low frequencies of *Rumex* and Chenopodiaceae. These spectra confirm the existence of a mixed temperate woodland in the region. The presence of a single grain of *Typha latifolia* indicates that summer temperatures exceeded 14°C (Iversen, 1944). Mild winters are indicated by the persistent presence of *Pteridium*.

Biozone Wo-2, which occurs in organic sediments with an increasing clastic content, includes a marked rise in *Corylus* pollen (up to 62%) and a decline in *Pinus* pollen (to 10%) (Fig. 3). *Ulmus*, *Alnus*, *Fraxinus* and *Acer* pollen continue at similar frequencies to the previous zone. Shrub and herb taxa occur in low frequencies. The sporadic appearance of *Hedera* points to a mild climate with winters of limited severity (Iversen, 1944; Zagwijn, 1996). The consistent presence of Chenopodiaceae pollen (ca. 2%) suggests that saltmarsh vegetation was present in the surrounding area.

Biozone Wo-3 coincides with a change in the stratigraphy, as the organic-rich sediments of Wo-2 are replaced by silty clays at 6.15 m (Fig. 3). The spectra are characterised by an abrupt rise in Chenopodiaceae pollen (5-10%), accompanied by a more gradual rise in Poaceae and Cyperaceae pollen. This points to the local development of a saltmarsh. Dinoflagellate cysts were also present in the pollen residues of this zone (Fig. 4) which suggests the continuing input of seawater. In the arboreal pollen assemblages, *Corylus* remains dominant but is less abundant than in zone Wo-2, whilst *Quercus* occurs at 15-24%. *Picea*, *Taxus*, *Carpinus*, *Ilex* and *Salix* pollen make their first appearance. The record of *Taxus* is noteworthy, indicating a mild oceanic climate and/or the development of calcareous soils further inland (cf. Deforce and Bastiaens, 2007). The presence of low frequencies of *Alnus* and *Salix* pollen reflects the occurrence of damp habitats, probably in adjacent areas of a floodplain. Overall, this assemblage indicates that intertidal or coastal wetland communities became fully established during this phase, with mixed thermophilous woodland persisting in the hinterland.

When considered as a whole, the pollen spectra are typical of the early temperate substage of an interglacial, a time when oak and other thermophilous forest taxa were expanding and later became established in the regional forest. This inferred period of climatic amelioration coincided with rising sea levels in the coastal area. The palaeoecological changes are in line with the observed lithofacies changes, in particular the replacement of organic sediments in Wo-1 and Wo-2 by silty clays in Wo-3 as tidal environments became established. Based on the dominance of *Corylus*, and the records of *Picea* and *Taxus*, an Eemian correlation is likely. The latter two taxa first appear in Eemian spectra in the

Netherlands and Belgium during pollen zone E-4 (Mostaert and De Moor, 1984, 1989; Zagwijn, 1996). The sparse records of interglacial tree pollen recorded between 7.28 and 11.60 m do not provide clear insights into the biostratigraphy of the sediments (Table 5). Taxa present are consistent with an early interglacial environment. The dinoflagellate cysts between 8.50 -11.60 m (Fig. 4) point to tidal activity which agree with the sedimentological interpretation; an environment with mixed tidal and fluvial influences (Table 2). However, some reworking of the dinoflagellate cysts from Paleogene strata, cannot be over-ruled.

It is interesting to note that an erosional boundary occurs in the sedimentary sequence at 7.87m. Whilst no other borehole data are available from the surrounding area to confirm whether this erosional surface is local or regional in extent, the deposits up to 1 m beneath this marker horizon are characterized by a high concentration of calcareous nodules. Their presence is suggestive of drier conditions that could have resulted from lowering of water tables during a period of non-deposition and/or prolonged exposure to subaerial weathering. Together the evidence suggests that this part of the core represents a significant hiatus of pre-Eemian age.

4.4. History of the valley incisions and infillings

The morphology of the top of the Paleogene substratum, the existence of regional erosional surfaces and the facies architecture of the Pleistocene valley fills in the WCP together attest to a complex environmental history. Five cycles of incision and valley infill are recognized (Fig. 5). The reconstruction of the successive erosional phases in combination with the stratigraphic position of the infills reveal an eastern migration of the valley systems until the third incision phase after which a widening of the valleys occurred both to the east and west.

4.4.1. Cycle I

The remains of the oldest and concurrently the shallowest incised valley occur in the vicinity of Lollege, ‘t Vosje and Lo (Fig. 1, 5), where the valley floor lies between - 0.7 m and – 2 m TAW. The sedimentological properties of the bottom part of the infill point to an important freshwater influx (Fig. 7). Similar observations are made in the mollusc and ostracods assemblages by Vanhoorne (2003) at Lo. Upward the infilling sequence, sediment characteristics and foraminiferal assemblages reveal a transition into an estuarine environment. In the valley-fill part that survived the subsequent erosion phase the top of the infill gives information concerning the relative sea level at that time. As on the one hand the upper sequence boundary lays only one metre below the present surface and on the other hand the infill took place in a subtidal and lower intertidal environment, relative sea level was at that time comparable, perhaps slightly higher to that at the present.

4.4.2. Cycle II

Remnants of the second incision phase and the subsequent infill are observed in the drilling Kellen (66W135) (Fig. 1, 7) where a depth of around - 8 m TAW is reached. There the basal part of the valley infill facies consists of high-energy fluvial sediments (until -5.26 m TAW), overlain by estuarine intertidal deposits. As next erosion only removed the eastern lying sediments the preserved deposits point to an approximately similar sea-level position as during the final stage of previous infilling phase.

4.4.3. Cycle III

In the central part of the WCP several cores record the presence of a third deeply incised valley, that attains a depth of – 18.5 m TAW (Fig 5, 8) and which is broadly north – south oriented (Fig. 2). As tidal channels of Holocene age have deepened and erased parts of third valley the northerly extension remains unknown. In this valley the infilling facies grade from estuarine deposits in the north into tidally influenced river deposits in the south. The most southern penetration of the tidal signature is registered in Rattekot (Fig. 1, 8). In few isolated niches in the north fine grained fluvial deposits are observed as lowermost infill facies. Fluvial sediments are currently observed as from Nieuwkapelle into southern direction, covering the whole or a great part of the record (Fig. 8).

4.4.4. Cycle IV

Both west and east of aforementioned valley evidence of the fourth palaeovalley is encountered. It has the same orientation as the previous one but extends further northwards, reaching the present-day coast via Wilskerke and Middelkerke (Fig. 1). This feature has a maximum depth of – 16 m TAW in the north and less than – 10 m in the south. The infill includes various type of estuarine deposits, from outer to inner estuarine deposits, and fluvial deposits. The fluvial sediments predominate the infilling sequence from Oudkapelle and further southward (Fig. 1). They are mainly fine grained, and include both channel and overbank sediments (infill IV – Fig. 8). However, signs of tidal penetration is observed as far as Woumen. In few places fluvial deposits are preserved as lowermost infill at the seaward side of the valley. Contrary to observations in Great Britain and France no coarse siliciclastic deposits are accumulated beside a coarse channel lag of maximum a few decimetres. The coarsest grain-size fraction consists of fine to medium fine sand.

4.4.5. Cycle V

Proof of the fifth and latest Pleistocene incision is found in a shallow valley extending beyond the eastern and western margins of the fourth valley (Fig. 5). The maximum depth is

–10 m. Given the dimension of the fifth incision, infill V has a spacious distribution in the WCP but consists exclusively of fluvial deposits (Fig. 7, 8).

4.5. Shallow marine environments at the northern margin of the incised-valleys systems

The WCP north of the line Adinkerke, Veurne, Wulpen, Nieuwpoort, Westende and Leffinge was part of a shallow marine environment. The bottom most section of the Pleistocene sequence is in the northwestern corner composed of shell-rich deposits up to 10 m, whereas east of Westende siliciclastic sand deposits are predominant. Upwards the sequence along the whole WCP, the shallow marine deposits are composed of sand in which the shell remnants are reduced to a minor component (Fig. 6). The sand sedimentation resulted, at least in the northwestern corner, in the development of a barrier creating a sheltered area on the landward side which supported tidal flats (Figure 8 in Bogemans and Baeteman, 2014). The above described shallow marine deposits prolongs into France, running between the Belgian border and Calais (Sommé et al., 2004). The stratigraphic position of these shallow marine deposits suppose a preceding stage in the transgressive phase to which infill cycle III is linked.

5. Discussion

On the basis of the pollen biostratigraphy of the Woumen core, infill IV took place during the Eemian Stage. The stratigraphic position of infill V in combination with the exclusive fluvial nature of the infill and the overlying marine Holocene deposits points out a Weichselian age of the infilling facies. A time indication for the aggradation phase of infill III is revealed by the lower most deposits of the Woumen core (below 7.86 m). Sedimentological results evidence the existence of an estuarine environment but the inland position of these estuarine deposits and an early interglacial pollen spectra are contradictory. In general, an inland extension of the tidal influence is related to an advanced transgressive phase which is hard to place in an early stage of an interglacial. A primary depositional context of the pollen is therefore unlikely, a statement that is supported by the investigated dinoflagellate cysts as those contain a lot of reworked species. Taken as a whole, the presence of Eemian temperate pollen in the overlying deposits of the Woumen core, the presence of an hiatus around 7.8 m depth and the estuarine nature of the deposits under study are all in favour of a pre- Eemian age.

Chronostratigraphic evidence for infill I is in the literature provided by Vanhoorne (1962, 2003). However, the author did not propose one unique chronostratigraphical interpretation (see 2.2). Bates et al. (2003) state in an overview study of marine deposits of the coasts of southern England, the British Islands and Northern France that the height above modern sea-level of the marine deposits of MIS 9, 7 and 5e age are the result of slow uplift of the coastal zone due to isostatic response to sediment unloading during the erosional phases and perhaps deep-seated tectonics. Antoine et al. (2003) seek an explanation in long term tectonic causes along both coasts of the Channel region and associate the Pleistocene uplift with the progressive tilting of Britain since the opening of the Atlantic Ocean and the subsidence of the North Sea. They estimate an uplift of 55 to 60 m per million years since the end of the Early Pleistocene in northern France. In Herzeele and the WCP no important tectonic faults are present and no differential tectonic movements, even tectonic activities are registered. Elements like the elevation difference between the deposits in Belgium (the vicinity of Lo – Lollege) and France of around 10 m (i.e. ca. + 10 m NGF (+ 12.29 m TAW) at Herzeele and ca. + 1 m TAW at Lo) over a distance of less than 25 km, the different depositional records and different lithological composition of the shell-bearing beds in both areas are not in favour of a similar age for both deposits. Besides, contrary to the location in Herzeele, in the WCP the nature of the mollusc taxa point to strong reworking. The work in this paper suggests that valley infill cycle I is younger than the Formation of Herzeele in France, with a maximum age of MIS 9. Their relative position as to the channel-fill shell-rich sediments of MIS 11 age in Herzeele is in agreement with observations made by e.g. Bridgland et al. (2001) and Roe et al, (2009, 2011) in the North Sea Basin and in other parts of the world (e.g. Bard et al., 2002; Dutton et al., 2009; Lea et al., 2002; Siddall et al., 2007). Worldwide is also observed that during both MIS 7 and MIS 9 sea-level peaked several time up and down (e.g. Bard et al., 2002; Dutton et al., 2009; Lea et al., 2002; Siddall et al., 2007; Waelbroeck et al.,2002). The downcutting processes of the oldest valleys could have been taking place during a glacial period *s.s.* or during one of the cold stages within the same MIS stage. At this moment an age indication for infill II and III is lacking, although a MIS 7 age for infill III is most likely.

The presence and distribution pattern of the shell-bearing and shallow marine sand deposits prove the existence of a transport pathway from the English Channel towards the North Sea, suggesting an open Strait of Dover at the depositional phase III. A pathway that is used until today during interglacial periods, (Anthony et al., 2010; Héquette & Aernouts, 2010; Reynaud & Dalrymple, 2012), except for the mud fraction (Zeelmaekers, 2011).

The valley system present in the WCP can be traced further seaward into the present-day nearshore area where it bends toward to west, running further parallel to the French coasts (Liu et al., 1992). The origin of the Strait of Dover is in common linked to two catastrophic outflows of North Sea glacial lakes formed during the Middle Pleistocene (e.g. Gibbard, 1988, 1995, 2007; Gibbard et al., 1996; Gupta et al., 2007; Hijma et al., 2012; Murton and Murton, 2012; Roep et al., 1975;). The first flood is situated during MIS 12, the second within MIS 6 (Busschers et al., 2008; Cohen et al., 2011, 2014; Toucanne et al., 2009). The extension of the MIS 12 glacial lake, as proposed by Gibbard (1995, 2007) and Cohen et al. (2011, 2014), implies the coverage of the Belgian coastal plain, then characterised by a higher topography than today. Deep valley incisions took place after MIS 12. During MIS 6 the WCP laid south of the lake shores as the dam forming the southeastern margin of the lake was situated northward near The Netherlands (Busschers et al., 2008; Hijma et al., 2012). In the WCP but also in the southern adjacent higher elevated area, the latter free of important erosional processes, no sedimentary evidence is present that endorse the presence of a lake or lake shore. Only aeolian and fluvial deposits are observed south of the WCP (this work and Bogemans and Baeteman, 2006).

6. Conclusions

The Pleistocene deposits underlying the present Belgian western coastal plain show a complex sedimentary history characterised by five cycles of incision and deposition. In the created incised- valley systems, the bottom of the oldest valley situates only a few metres below the present-day surface. Although palynological analyses do not provide a uniform chronostratigraphic correlation, a MIS 9 age is most plausible for these oldest infill facies. A correlation with the Herzeele Formation as proposed by Vanhoorne (2003) is disclaimed. The second and third incision got deeper each time, the latter attaining a depth of -18.5m. Palynological and sedimentological evidence suggests infilling phases predating the Eemian. During the aggradation period of infill III the coastline extended more inland than ever since. Shallow marine sediments accumulated along the present day coast of both northern France and Belgian and are respectively defined as the Loon and Oostende Formation (Table 1). The Eemian age proposed by Baeteman, 1993; Denys et al., 1983; Gullentops et al., 2001;

Mostaert & De Moor, 1984; Mostaert et al., 1989; Paepe, 1971; Sommé et al. (2004) and Sommé (2013) for these deposits is no longer sustainable. The infill of the fourth and fifth incised valley date from the Eemian and Weichselian respectively. The reconstruction of the successive erosional phases in combination with the stratigraphic position of the infills reveal an eastern migration of the incised-valley systems until the third incision phase where after a widening of the valleys happened both east and westward. In addition, the incision depth of the two youngest valleys decreased consecutively from - 10 m to – 5m TAW inland. The youngest valley covers the greatest part of the western coastal plain.

The Pleistocene records of the western coastal plain support the presence of " an open" Strait of Dover. Remains of late Middle Pleistocene proglacial lake deposits as suggest by for example Cohen et al. (2011, 2014); Gibbard (1988, 1995, 2007); Gibbard et al. (1996); Hijma et al. (2012); Roep et al., (1975) are not observed in the study area and in the southern adjacent area.

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